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State-of-the-Art Technologies on Low-Grade Heat Recovery and Utilization in Industry

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Abstract

To improve energy efficiency in industry, low-grade heat recovery technologies have been advanced continuously. This chapter aims to provide a basic understanding of state-of-the-art technologies for low-grade heat recovery and utilization in industry, which are developed based on the concept of thermodynamic cycles. The technologies include adsorption, absorption, liquid desiccant, organic Rankine cycles (ORC), and Kalina cycles. The definition of low-grade heat sources, the working principle, recent advances in research and development (R&D), and commercial applications of the technologies (if any) will be discussed, followed by concluding remarks on advantages and disadvantages, future outlook, barriers, and opportunities.

Keywords: industrial low-grade heat, adsorption, absorption, liquid desiccant, organic Rankine cycle, Kalina cycle

1. Introduction

Energy-related issues including energy resources, prices, demand, supply, and use always attract global attention. In particular, international governments from developed nations such as the US and UK have constantly allocated substantial budgets to carry out contemporary evaluations on relevant issues either on national or international levels. Two recent examples include the International Energy Outlook 2018 [1] by the US Energy Information Administration and the independent assessment delivered by the UK Committee on Climate Change [2] as requested by the UK Government. To indicate the seriousness of energy issues, [1] projected that world energy consumption in 2040 would reach up to 736 quadrillion British

thermal units (Btu) where industry sector (which would show an 18% increase from 2015 to 2040) would attribute to more than 50% of the total world energy consumption. In the UK context, the Government has set a national target to achieve more than 20% of improvement in industrial energy efficiency by 2030 [2]. To support long-term energy efficiency improvement, action plans are also established, for instance, enabling innovation and dialog for finance access improvement opportunities.

Exploiting the utilization of industrial waste heat and adopting more thermally efficient practices are examples of possible ways to improve industrial energy efficiency [3]. During industrial processes e.g. drying, heating and combustion, waste heat presents in the forms of vapor, fume, exhaust, waste water and heat; and is discharged from furnaces, motors, refrigeration systems, boilers etc. on without further utilization. The temperature of waste heat varies with industrial processes and the range is very broad, from as low as 30°C to more than 1000°C. Accordingly, waste heat is generally distinguished as high-, medium- and low-grade heat. Compared to medium- and high-grade heat, utilizing and recovering low-grade heat is far more challenging, less feasible and not commonly applied in practice. It is worth noting that low-grade heat has the potential to be utilized in producing (i) electrical power; (ii) heating; (iii) cooling; (iv) heating, cooling, and electricity simultaneously; (v) fresh water; and (vi) hydrogen [4], with the deployment of advanced technologies.

This chapter aims to provide a basic understanding of the state-of-the-art technologies including adsorption, absorption, liquid desiccant, organic Rankine cycles (ORC), and Kalina cycles, which are developed based on the concept of thermodynamic cycles for low-grade heat recovery and utilization in industry. Following the definition of low-grade heat sources in Section 2, the working principle, recent advances in research and development (R&D) and commercial applications of each technology are presented in Section 3. This chapter is closed with concluding remarks on advantages and disadvantages, future outlook, barriers, and opportunities. By providing insights and strengthening knowledge in the subject, this chapter will be beneficial to engineering students, researchers and industrial practitioners.

2. Definition and potential sources of industrial low-grade waste heat

During industrial processes, heat is transferred between heat sources and heat sinks. Low-grade waste heat and low-grade heat sources have been defined in literature where the definition applied in this chapter is adopted from [4]. In brief, low-grade waste heat is the (process) heat that is discharged to the environment as its recovery and utilization within the processes is not viable. Meanwhile, low-grade heat sources are the waste heat sources, which have a temperature ($T_{\text{low-grade heat source}}$) higher than the sum of the temperature of the heat sink (T_{sink}) and the minimum allowable temperature difference in the system (ΔT_{min}) but not high enough to break through the minimum temperature required for viable heat recovery ($T_{\text{viable min}}$, which is 250°C). In other words, low-grade heat sources are the waste heat sources with a temperature

ranging between $T_{\text{viable min}} + \Delta T_{\text{min}}$ and $T_{\text{viable min}}'$ that is, $T_{\text{viable min}} + \Delta T_{\text{min}} < T_{\text{low-grade heat source}} < T_{\text{viable min}}'$. **Table 1** presents the temperature ranges of numerous industrial low-grade waste heat sources. Among all, flue gas from boilers, waste heat from compressor cooling systems and condensate from both steam heating and spent cooling water are common waste heat sources across all industrial sectors. Other waste heat sources are industrial sector specific. Most industrial waste heat sources have temperatures below 175°C rather than approaching $T_{\text{viable min}}'$ i.e. 250°C.

Low-grade waste heat source		Temperature (°C)
Generic unit/process		
1. Boilers [5, 6]	• Flue gases	110–260
2. Air compressors [7]	• Waste heat from compressor cooling system	30–60
3. Heating/cooling network [7]	• Condensate from steam heating and spent cooling water from cooling systems	60–90
Industrial sector		
1. Petrochemical [5]	• Stack gas from crude distillation	156
	• Stack gas from vacuum distillation	216
	• Exhaust from ethylene furnace	149
2. Iron/steel making [5]	• Waste gas from coke oven	200
	• Blast furnace gas	93
	• Blast stove exhaust	250
3. Aluminum [5]	• Exhaust from aluminum casting with a stack melter	121
4. Food and drink [7]	• Extracted air from cooking with fryers or ovens	150–200
	• Exhaust from drying with spray/rotary dryers	110–160
	• Water vapor from evaporation and distillation	100
5. Textile [6]	• Dyed waste water from drying	90–94
	• Stenter exhaust for fabric drying and finishing	180
	• Waste water rejected from heat exchangers	58–66
6. Paper [8]	• Waste steam from slag flushing in furnace	95–100
	• Waste water from slag flushing in furnace	65–85
	• Cooling water from furnace wall cooling	35–45
7. Cement [9]	• Exhaust from cement kilns using 5- or 6-stage preheaters	204–300
	• Hot air discharged from clinker coolers	100

Table 1. Low-grade waste heat sources and temperatures.

3. State-of-the-art technologies for low-grade heat utilization

3.1. Vapor compression

Generally, vapor compression systems [10], which are also referred to as mechanical or refrigerative compressors have been established as the most mature machines for cooling, heat pumping and/or dehumidification purposes. As illustrated in **Figure 1**, a typical vapor compression system consists of a refrigeration circuit (which is made up of an evaporator, a condenser, a compressor, and an expansion valve) and an air circulation fan. Water, R407c and R134a are the refrigerants, which are commonly used as the working fluids of commercial vapor compression systems. When air is drawn to the evaporator by the fan, the low-pressure, low-temperature liquid-vapor refrigerant mixture coming from the expansion valve extracts heat from the air; the liquid refrigerant evaporates and the air is cooled. Leaving the evaporator, the saturated refrigerant vapor is compressed to high-pressure superheated state, which dumps condensation heat in the condenser. If in a dehumidifier, the high-temperature, high-pressure superheated refrigerant vapor is condensed by the cool but dry air from the evaporator, heat is rejected and the air becomes dryer and warmer. To run the fan and the compressor, electricity is consumed intensively. As vapor compression systems are conventional technology, they are not further discussed in this chapter. More details are available in [11].

3.2. Adsorption

Adsorption is the enrichment or depletion of one or more components in an interfacial layer between adsorbent and adsorbate, as defined by International Union of Pure and Applied

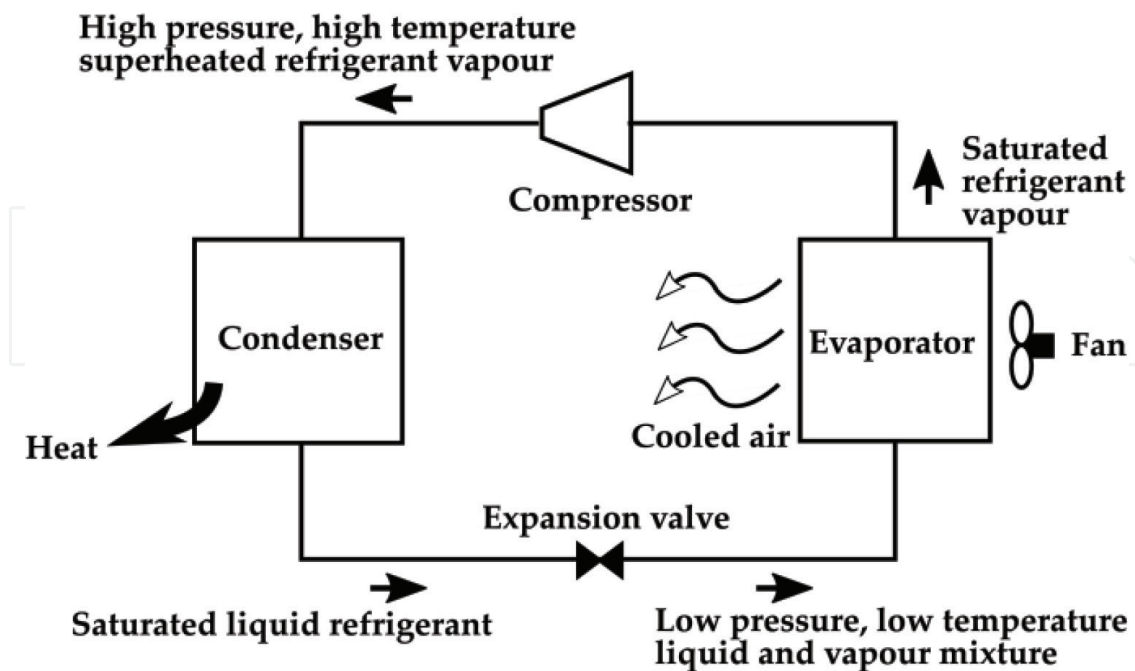


Figure 1. A schematic diagram of a traditional vapor compression system.

Chemistry [12]. There are four types of adsorption depending on the interface: solid-gas, solid-liquid, liquid-liquid, and liquid-gas. The solid-gas adsorption has been extensively used and studied in recent decades and is often referred to adsorption or solid sorption [13]. If the solid-gas binding force involves intermolecular forces, i.e. Van der Waals forces, it is categorized as physical adsorption (physisorption) and the typical physisorption working pairs are silica gel-water [14], activated carbon-ammonia or methanol or ethanol [15], zeolite-water [16], etc. If the coordination reaction takes place on the exposed surface forms a strong ionic or covalent bond between the adsorbate and the adsorbent, it is recognized as chemical adsorption (chemisorption) that consists of mainly two types of working pairs for low-grade heat utilization: metal halides-ammonia [17] and salt hydrates-water [18]. In other words, multi-layers (in physisorption) or monolayer (chemisorption) of adsorbate accumulates on the surface of an adsorbent during an adsorption.

The fundamental principle of an adsorption refrigeration cycle is schematically by a basic adsorption unit shown in **Figure 2**, where reversible sorption process operates or chemical reaction performs in an intermittent manner. Low-grade heat is supplied to the adsorbent bed to break the binding force between the adsorbent and the adsorbate (refrigerant) as the adsorbate (refrigerant) gas is desorbed from the adsorbent bed and heading for the refrigerant container that acts as a condenser. Such a process is referred to endothermic decomposition as shown in **Figure 2(a)**. When the decomposition is finished, two vessels are isolated from each other for an internal prior to the exothermic synthesis. Once sufficient pressure difference has been built up between these two vessels and there is a need of refrigeration, as soon as two vessels are connected in **Figure 2(b)**, driven by the pressure difference the adsorbate inside the refrigerant container (becomes evaporator in this process) evaporates and is adsorbed inside the adsorbent bed. The evaporation of the refrigerant provides the refrigeration power, and the adsorption heat of the adsorbent bed is to be released to the proper heat sink. For heating purpose in two types of heat pump applications, (1) adsorption unit can perform as a heat multiplier to produce a large quantity of medium temperature heat through both the condensation and synthesis process at the cost of a small quantity of high-temperature heat input for the decomposition [19]; or (2) in a heat transformer it can deliver concentrated high-temperature heat through synthesis process if both decomposition and evaporation processes are provided with medium temperature heat [20].

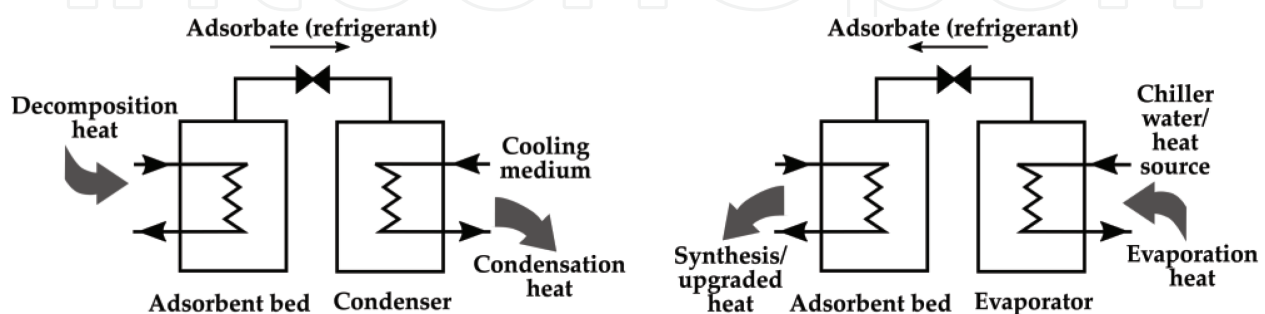


Figure 2. (a) Endothermic decomposition (left) and (b) exothermic synthesis (right).

Adsorption heating and cooling application have been widely developed in the past decade. Various advanced cycles have been developed for improvement in energy efficiency of thermal energy recovery and utilization in a wider temperature range e.g. cycles with heat and mass recovery, multi-stage, multi-sorbent, and cascaded cycles, etc. [21]. Considerable effort has been also focused on the development of composite adsorbent materials to enhance heat and mass transfer properties, improve adsorption capacity and enlarge specific power [13]. Especially, physisorption type air conditioning and heat pumping machines developed by some European and Japanese companies are on or near-market currently (SorTech, GBU mbH, Invenso, Mayekawa chillers; Vaillant and Viessmann heat pumps, etc.). Meanwhile, substantial R&D effort has been put on water-based adsorption systems for such as dehumidification/drying and desalination application. The first worldwide adsorption water desalination and cooling plant has been implemented in Riyadh, Saudi Arabia since 2016, and the process has a cooling capacity of up to 1 MW and desalinated water production up to 100 m³/day. With the inherent nature of intermittency, adsorption cycle also presents itself as a promising solution for energy storage as the decomposition is charging energy and the synthesis is the energy discharging process. Such an adsorption energy storage system is superior to the methods of sensible and latent heat storage not just because of its high energy density but also its low energy loss during long-term storage [22] as the binding energy is stored independently of the time span between decomposition (charging process) and synthesis (discharging process). With ever increasing energy prices and greater environmental concerns it can be expected that adsorption refrigeration and heat pumping will soon join the mainstream technologies.

Adsorption power generation concept, especially ammonia-based adsorption cycle which has greater potential of productive power generation than water-based types due to the higher working pressure, has recently started to attract interest for more versatile application, as the adsorption unit integrated with turbine or expander can convert thermal energy to mechanical work, or produce electricity when a generator is attached [23]. Modeling, simulation, and experimental investigation have been conducted and demonstrated the feasibility of the adsorption cogeneration of cooling and electric power [24, 25]. Most recently, a new dual energy storage system through the integrated ammonia-based resorption cycle is being developed for simultaneous electric and thermal energy storage [26, 27] as illustrated in **Figure 3**. In the energy charging process, mechanical or electrical power is stored together with the ultra-low-grade thermal energy (~100°C) as the ammonia (refrigerant) is desorbed in the endothermal decomposition and further pressurized through vapor compression driven by mechanical energy or electricity. In the energy discharging process, the stored energy can be delivered as either heating or cooling power as the conventional adsorption cycle promises, or even mechanical energy if the transferred high-pressure ammonia passes through a turbine or expander. In fact, when the integrated system restores mechanical energy, it would also generate a considerable quantity of upgraded thermal energy, plus a small quantity of cold energy depending on heat source temperature and the refrigeration requirement, as so-called the Tri-generation Recovery and Efficient Energy Storage (TREES) concept [26]. In contrast with conventional chemisorption systems, the TREES cycle embraces broader application with higher penetration of renewable energy; not just utilizing thermal energy (waste heat, solar energy, or geothermal energy) but also potentially storing intermittent electric power from solar PV and wind power or off-peak cheap electricity.

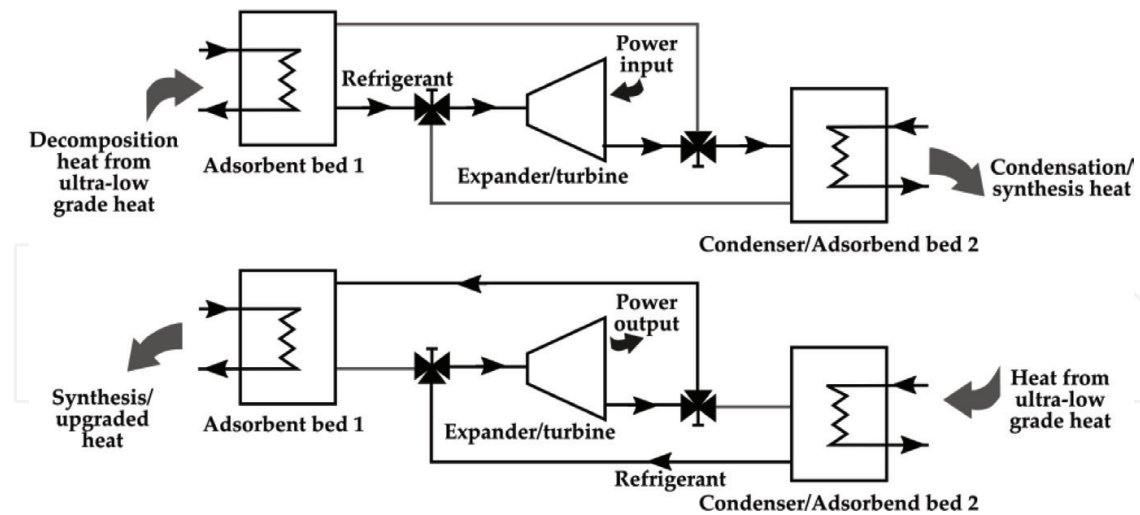


Figure 3. (a) Ultra low-grade heat input (top) and (b) power generation (bottom).

3.3. Absorption

Absorption is a process where a device (i.e. an absorber) is used to enable any substance (i.e. an absorbent, also referred to as an “absorption medium”) to soak up or take in another substance e.g. liquid or gas (i.e. an absorbate). In other words, an absorber enables an absorbent to absorb an absorbate during absorption. To differentiate from adsorption, in absorption process the molecules of the absorbate penetrate the surface layer and enter the structure of the bulk solid or liquid, causing the change of the composition of one or both bulk phases [28]. The absorption process using liquid absorbent and gas absorbate has been applied in refrigeration industry and also successfully adopted in commercial chillers and heat pumps for a long period. A liquid-gas absorption heat pump system (heat multiplier) is illustrated in **Figure 4**, consisting of a solution and refrigerant loops as the absorbate is also referred to as a refrigerant.

The key components of an absorption system include a generator, an absorber, a condenser and an evaporator whilst a heat exchanger, a solution pump, and expansion valves are commonly incorporated. The working fluid is made of an absorbent-refrigerant solution, which presents in the generator and the absorber. Lithium bromide-water ($\text{LiBr-H}_2\text{O}$) and water-ammonia ($\text{H}_2\text{O-NH}_3$) are two absorbent-refrigerant solutions commonly chosen for absorption systems. For an absorption cooling system, in the absorption loop, the solution weak in refrigerant leaves the generator as its temperature and pressure are lowered by the heat exchanger and the expansion valve respectively before entering the absorber where absorption takes place and the refrigerant is absorbed, which releases absorption heat to the surroundings. The solution strong in refrigerant from the absorber is then pumped and preheated before entering the generator. In the refrigerant loop, high-pressure refrigerant vapor from the generator condenses in the condenser and releases heat to the surroundings. The pressure of the refrigerant liquid is lowered by the expansion valve before it reaches the evaporator and evaporates. The low-pressure refrigerant vapor then enters the absorber where the vapor is absorbed. As the working fluid is regenerated in the generator and the absorption in the system repeats continuously, the quantity of the solution remains the same. In addition to utilizing waste heat for

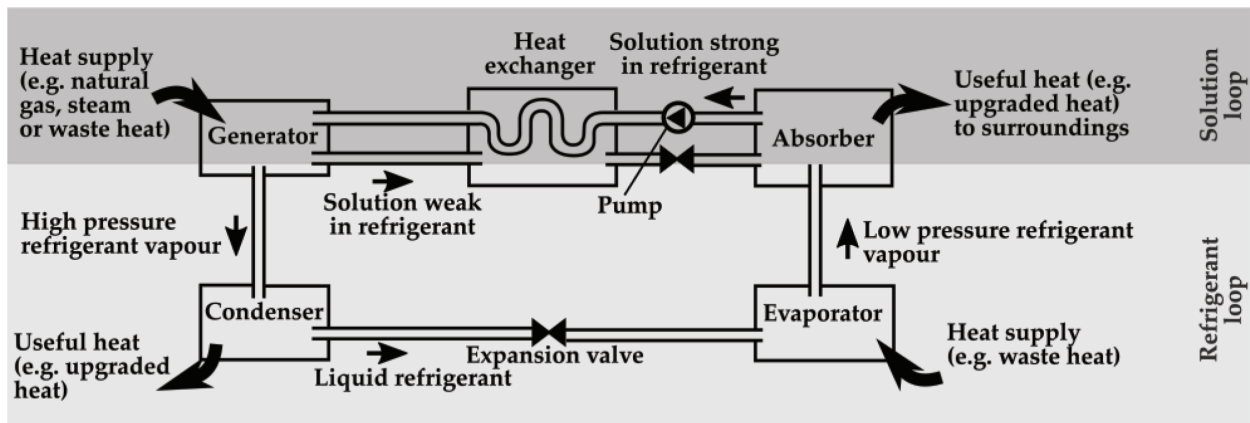


Figure 4. The schematic diagram of an absorption heat multiplier.

solution regeneration in the generator, industrial low-grade waste heat can be supplied to the evaporator to assist the evaporation processes of the refrigerant in a heat transformer so that the upgraded heat can be gained from the absorber; or in a heat multiplier, condensation and absorption processes in the condenser and absorber respectively can be collected for further utilization.

Various modifications have been proposed to advance absorption systems for enhanced capacity, improved coefficient of performance, and increased temperature lift for heating or temperature drop for cooling. For instance, the system can be simplified to form an open-cycle absorption heat pump by removing the evaporator and bringing the solution in the absorber in direct contact with the absorbate source (e.g. moist air, waste vapor, or exhaust flue, etc.) to release the absorption heat [29]. When solution and refrigerant tanks are additionally incorporated to absorption systems, the systems work as absorption heat storage systems [30]. Two or three absorption systems can be coupled with each other in series to form a two- or three-stage absorption heat transformer by recovering the absorption heat of one system for the generation and vaporization heat of the next system (and so on) [30]. Also, an absorption system can deploy high- and low-pressure absorbers, to form a double absorption heat transformer. The low-pressure absorber also acts as an additional evaporator where the adsorption heat is used to vaporize the refrigerant vapor that is to be absorbed by the high-pressure absorber [30, 31]. A double-effect absorption heat transformer employs two generators as the high-temperature refrigerant vapor generated from the high-pressure generator is recovered to provide the low-pressure generator with generation heat, thus two streams of refrigerant vapor from two generators converge in the condenser [31]. There are also researches on 1.X (or variable) effect cycles that can flexibly perform in larger working range with higher energy efficiency [32]. The combination of an absorption system and a traditional heat exchanger, as so-called absorption heat exchanger, can realize larger temperature drop through heat exchange, i.e. the outlet temperature of the cold fluid becomes higher than the outlet temperature of the hot fluid [29]. In relation to the working fluid of the systems, the use of alternative mixtures e.g. water-ternary hydroxides, water-lithium iodide, ammonia-sodium thiocyanate, ammonia-ionic liquid etc. have been explored. More details are available in [29, 30].

3.4. Liquid desiccant systems (LDSs)

Solid or liquid desiccant materials can be used in industry for dehumidification and cooling purposes. Desirable characteristics required for desiccants include low vapor pressure, regeneration temperature, crystallization point, viscosity and cost with high density [33]. Whilst silica gel, zeolites, aluminas and polymers are solid desiccants, organic desiccant e.g. tri-ethylene glycol (TEG) and inorganic salt solutions such as LiBr, lithium chloride (LiCl), and calcium chloride (CaCl_2) are examples of liquid desiccants [33, 34]. LDSs involve liquid-gas absorption. They have the edge over solid desiccant systems as they can operate at regeneration temperatures, which are very low and they show higher thermodynamic coefficient of performance with lower pressure drops [35]. Compared to traditional vapor compression systems, apart from the advantages of being environmental friendly and heat driven LDSs are more flexible in temperature and humidity controls [34].

An LDS employs (i) a desiccant as a working fluid; (ii) two towers (also referred to as columns) which serve as a dehumidifier (i.e. an absorber, also referred to as a conditioner) and a regenerator respectively for air dehumidification and desiccant regeneration processes; (iii) devices e.g. pumps and fans for desiccant solution circulation; and (iv) a heat source and a heat sink (e.g. low-grade heat and a coolant) to heat up and cool down desiccant solution. **Figure 5** shows a typical LDS design. The strong desiccant solution is sprayed on top of the absorber whilst the wet, cool air used by industrial processes (referred to as “process air”) is drawn into the absorber by a fan. The water vapor pressure of the strong solution is lower than that of process air. When the strong solution contacts with process air directly, the difference in the water vapor pressures results in mass transfer i.e. the strong solution absorbs moisture from the process air and becomes weak whilst it is chilled (by a coolant). The weak desiccant solution is heated (by a low-grade heat, hot water or renewable energy sources) and sprayed into the regenerator and heated (by a low-grade heat) whilst regeneration air is circulated by a fan. The water vapor pressure of the weak solution is higher than that of regeneration air. When the weak solution makes contact with regeneration air directly, the

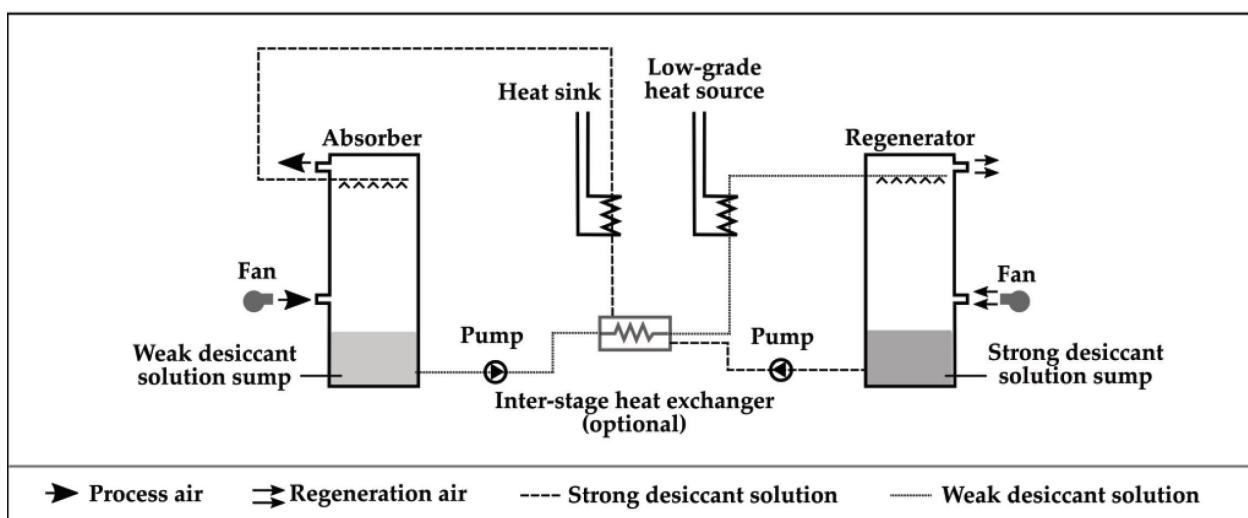


Figure 5. A schematic diagram of a LDS.

difference in the water vapor pressures results in mass transfer i.e. the weak solution releases moisture to regeneration air and becomes strong. An inter-stage heat exchanger may be used to chill or preheat the desiccant solution before entering the absorber and the regenerator.

R&D has been advanced in connection to the design of the towers, flow directions, liquid desiccant materials and system design. Following the introduction of membrane-based LDSs, towers applied for LDSs can be classified as randomly or structured packed, spray, wetted wall (also referred to as falling-film), and hollow fiber or parallel-plate membrane based (also referred to as membrane modules or membrane contactors), as illustrated in **Figure 6**. The directions in which the solution and the air enter and leave the towers distinguish the flow i.e. counter flow if both are in opposite directions and cross/parallel flow if both are in the same direction. To improve performance and cost-effectiveness, composite desiccant materials such as silica gel or SiO_2 impregnated with an inorganic salt (including CaCl_2 , LiCl , LiBr , SrCl_2 , and NaSO_4) have also been explored [36]. To enhance heat and mass transfer between desiccant solution and air, multi-stage LDSs have been proposed by [37], which operates in a cascade way to cool the solution in multiple stages when it flows through more than one absorber. Moreover, a pilot study has been carried out in power plants to investigate an LDS application, which integrates with a CO_2 capture system for moisture recovery [38]. Recently, vertical and horizontal discharge dehumidifiers, fiberglass packed regenerators and small packaged dehumidifier-regenerator commercial LDSs have been made available by Alfa Laval Kathabar [39].

3.5. Organic Rankine cycles (ORC)

An ORC is an emerging prime mover technology, which recovers low-grade heat for power generation. As a derivative of the conventional steam Rankine cycle, a basic ORC consists of four main components, as shown in **Figure 7**, including an evaporator, an expander, a condenser, and a feed pump. In the system, the working fluid at its lowest temperature and

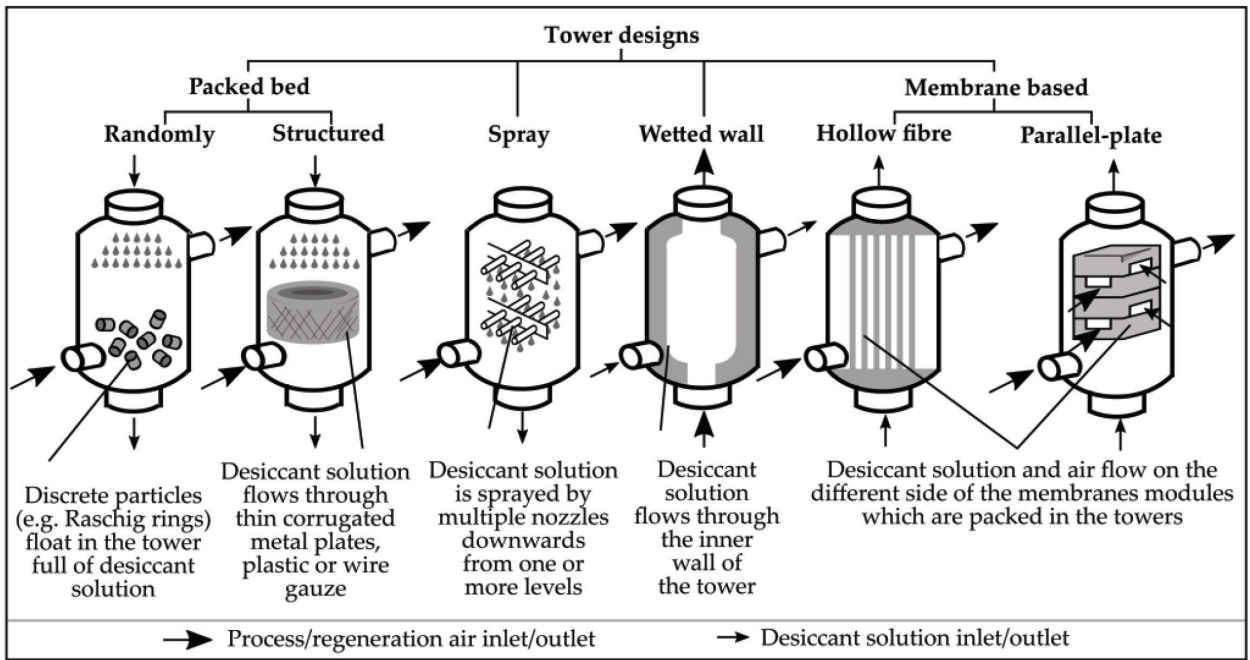


Figure 6. Various tower designs for absorbers and regenerators to enable heat and mass transfer between desiccant solution and process or regeneration air.

pressure is pumped by a feed pump to achieve the required pressure (maximum pressure in the cycle) before it goes into an evaporator where the working fluid is isobarically heated to form dry vapor. The dry vapor enters an expander where expansion takes place to generate mechanical work. The expander is connected to a generator where the resulting work is converted into electric power. Leaving the expander, the working fluid, which is now a mixture of vapor and liquid at minimum pressure, cools down in a condenser. The saturated liquid from the condenser flows into the feed pump and the cycle repeats.

The working fluids of ORCs are organic compounds, which have lower boiling points, critical points, specific volumes, and viscosity values than water. They can be classified as organic refrigerants, hydrocarbons, and siloxanes. Each works well for different heat source temperatures i.e. organic refrigerants are suitable for temperatures between 100 and 175°C; hydrocarbons for 175–250°C; and siloxanes for 250–400°C. As industrial waste heat sources are generally below 175°C, organic refrigerants are more ideal for applications. Some working fluids with low supercritical temperatures, such as CO₂ (the critical pressure and temperature at 73.8 bar and 31.1°C) and hydrocarbons, have been studied for ORC systems, as the cycles operate at supercritical condition, and therefore is known as the supercritical Rankine cycle (SRC). Because SRCs bypass a two-phase region during the heating process, they have a better thermal match with a heat source which results in less irreversibility. After expansion, the working fluid exiting the turbine can be purely superheated in vapor form or as a mixture of vapor and liquid [40].

Using pure fluids as the working fluid of ORCs involves isothermal condition in the boiler and the condenser, which creates a bad thermal match between the working fluid and the heat source or heat sink, leading to large irreversibilities. The issue can be diminished by adopting a mixture of working fluids (also referred to as “multi-component fluids,” “fluid blends,” or “binary mixtures”), such as zeotropic mixtures. This is because working fluid mixtures can offer a boiling temperature range rather than a boiling point at constant pressure. Likewise, SRCs using zeotropic mixtures potentially have further reduced exergy destruction during both boiling and condensation, leading to higher efficiency.

To safeguard the overall performance of ORCs in particular when the application scale is small and the temperature of heat sources is low, expanders play a key role, and therefore, have been researched for highly efficient design. To date, expanders proposed for ORCs can be classified as velocity- or volume-type [41], which show different characteristics. Velocity-type expanders e.g. axial turbine expanders possess higher flow rates but contain lower pressure ratios, rotational speeds, and tolerance of a two-phase condition at the outlet. Volume-type expanders e.g. screw expanders, scroll expanders, and reciprocal piston expanders are simpler with less moving parts, a wider power output range, and require less maintenance. The selection should be made by taking account of cost, efficiency, operating conditions, noise level, safety and leaking issues.

Various configurations with the potential of higher energy efficiency have been explored in R&D. When a regenerator (also known as feed-water heater, preheater, recuperator, and internal heat exchanger) is deployed to achieve a better thermal match between the working fluids and the heat sources, the working fluid will be preheated before entering the evaporator using either the vapor exiting the turbine or via the turbine bleeding during expansion. Such ORC configuration is referred to as a regenerative ORC. Also, one or more flash evaporator

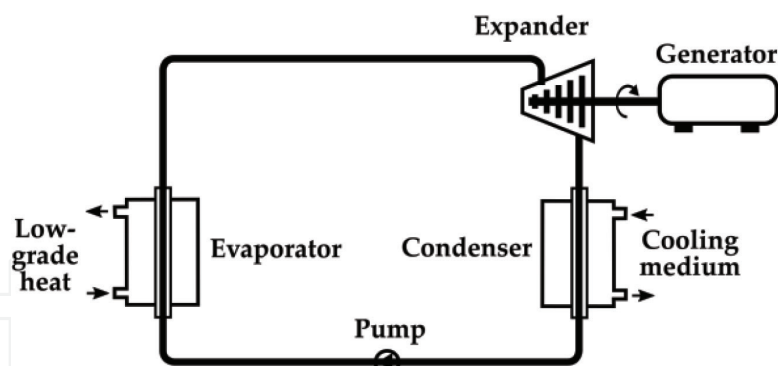


Figure 7. The schematic diagram of an ORC.

can be incorporated in an ORC to form single-, double-, or multiple-stage organic flash cycles, in which the working fluid of an ORC is flash evaporated before the gas vapor entering the expander. When more than two separate stages are incorporated in an ORC to enable the condenser of Stage 1 acting as the evaporator of Stage 2 (and so on), the configuration is known as a cascade ORC. More details can be found in [42].

To date, a number of ORC manufacturers (e.g., Turboden, Opcon Powerbox, and EXERGY) and commercial applications in industry sectors have been reported. To recover waste heat from furnace exhaust, the ORC units manufactured by Turboden have been operated by iron and steel foundries, including (i) Fonderia di Torbole in Italy since 1996; (ii) Toscelik Hot Strip Mill in Turkey with a 1000 kW net electric power output since 2011; (iii) NatSteel in Singapore with a 555 kW gross electric power output since 2013; (iv) Elbe-Stahlwerke Feralpi in Germany with a 2700 kW gross electric power output since 2013; and (v) ORI Martin in Italy with a 1900 kW gross electric power output since 2016 [43]. In Sweden, a NH_3 based, fully automated, remotely controlled ORC system supplied by Opcon Powerbox has been recovering low-grade heat from wastewater stream originated from the manufacturing processes in the Munksjö pulp mill since 2010, which produces electricity with a net output capacity of 750 kW_{el} [44]. ORC systems manufactured by EXERGY have been operated in three glass manufacturing plants of Sisecamin in Italy, each with a capacity of 5 MWe electricity [45]. According to [46], recovering industrial waste heat using ORCs commercially is limited to 10 applications around the world with a total installed power of 29 MW_{el}, and therefore, the market is still in its infancy.

3.6. Kalina cycles

Kalina cycles can recover industrial waste heat ranging between 80 and 400°C for power generation. In principle, Kalina cycles are absorption-based power generation cycle. Kalina cycles show superior performance over ORCs and supercritical cycles. Irresibility is scaled down as Kalina cycles reduce the heat transfer temperature difference between its working fluid i.e. ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) and heat source. Moreover, the Kalina cycle has one more degree of freedom than the Rankine cycles to be flexibly adopted to match with a certain heat source and heat sink, as the $\text{NH}_3\text{-H}_2\text{O}$ composition can be adjusted as well as the system high- and low-pressure levels. Other benefits of using $\text{NH}_3\text{-H}_2\text{O}$ as the working fluid include (i) enabling

efficient use of low-grade heat for vapor generation at higher pressure; (ii) less oxidation due to extremely low oxygen levels within the mixture, therefore, standard materials like carbon steel and standard high-temperature alloys can be used to handle ammonia [47].

To suit heat source characteristics and accommodate specific applications, more than 30 configurations, that is, Kalina Cycle Systems (KCSs) 1–34 have been introduced to date [45]. **Figure 8** depicts the system configuration developed for waste heat recovery in cement industry, which is based on KCSs 1–2 for power generation [48]. Low-grade heat is fed to the vapor generators respectively to boil and superheat the working fluid. The superheated vapor expands in the turbine to generate electrical power. The turbine exhaust is cooled down when passing through one of the recuperative heat exchangers, diluted by the working fluid from the vapor separator and condensed in the low-pressure condenser. Some saturated working fluid from the condenser passes through the other recuperative heat exchanger before reaching vapor separator while the remaining mixes with the vapor steam from the separator to form ammonia-rich working fluid. It is condensed in the high-pressure condenser by the cooling medium before being pumped back to the heat recovery vapor generators. As ammonia and water have close molecular weights, Kalina cycles do not require specific equipment design and piping system. Due to the lower boiling points of the mixture, a higher turbine inlet pressure and lower mass flow rate are permissible for Kalina cycles, which helps to minimize the running costs of the system. KCS-11 is the most suitable cycle for low-grade heat between about 121 and 204°C and KSC-34 or KSC-34 g are popular for application with heat source temperature below 121°C. More details can be found in [42].

System development, modeling, and experimental studies, which analyze the working fluid (including zeotropic mixtures), thermodynamic performance (i.e. entransy, entropy, and/or exergy), and parametric optimization of the cycles have been extensively researched over the years. Substituting an ejector for the absorber and the throttle valve has been proposed to reduce the pressure of the expander exhaust, which results in a larger difference in the working pressure of expansion [49]. As such, thermal efficiency and the power output of Kalina cycles are improved. Also aiming for greater power output, Kalina-Flash cycles have been introduced [50] where a flash vessel is incorporated into the cycles to produce secondary NH_3 -rich vapor by depressurizing the NH_3 -poor solution. Recently, Kalina cogeneration cycles [51] integrating an ejector have been developed to improve system performance and produce power and refrigeration simultaneously.

Focusing on industrial waste heat recovery, recent R&D direction has steered toward comparing ORCs and Kalina cycles. For instance, recovery of multiple heat streams in the process industry has been compared based on three waste heat patterns [52], which shows that the Kalina cycles are more superior when the temperatures of the heat streams form a linear relationship or increase slowly with enthalpy but become inferior if the temperatures increase rapidly. R&D has also advanced to integrate an ORC and a Kalina cycle to recover waste heat from the exhaust of a natural gas power generation system using the combination of solid oxide fuel cells and a gas turbine while the cryogenic energy of liquefied natural gas (LNG) is used as the heat sink, which shows an acceptable thermal efficiency with reduced exergy loss through temperature matches between heat sources and heat sinks [53].

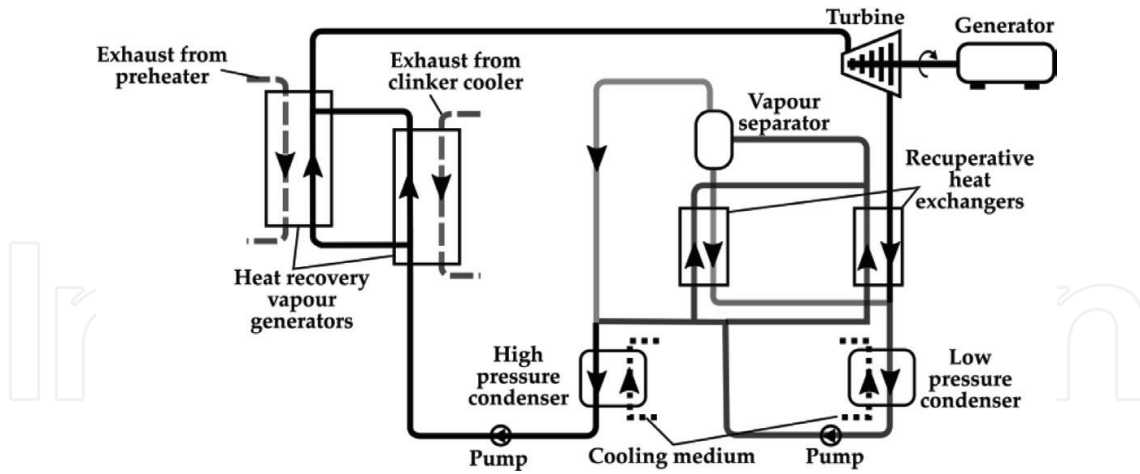


Figure 8. The schematic diagram of KCSs 1–2 developed for cement industry application.

Existing industrial waste heat recovery applications include [54] (i) 3.5 MW Sumitomo plant in Japan from 98°C hot water since 1999; (ii) 2.0 MW Kalina plant in Husavik, Iceland using geothermal brine at 124°C since 2000; (iii) 4.0 MW Fuji Oil plant in Japan from 116°C condensing vapors since 2005; (iv) 8.6 MW DG KHAN plant in Pakistan from the gas and air rejected from the kiln since 2013; and (v) 4.75 MW Star Cement plant in Dubai from hot air from kiln since 2013. Still, commercial application of Kalina cycles are limited due to a few practical issues (on top of expensive capital investment), including (i) the requirement of an accurate evaporation ratio in the boiler; (ii) the tendency of $\text{NH}_3\text{-H}_2\text{O}$ mixture to prematurely condense during expansion; (iii) requirement of low condensation temperature for productive generation; and (iv) the patents of Kalina cycles.

4. Concluding remarks

The technologies discussed in this chapter bring both advantages and disadvantages, as summarized in **Table 2**.

R&D has been ongoing to resolve technical constraints and enhance coefficient of performance of the state-of-the-art technologies. To achieve a low-carbon future, it is envisaged that R&D for these low-grade heat utilization and recovery technologies will continue to carry out more experimental studies, investigate working fluids and materials, examine thermodynamic properties (including energetic, exergy and entransy analyzes), cover performance analysis and optimization, develop and verify modeling with experimental results, propose new system design, integrate technologies with renewable sources and compare alternative systems or technologies. As evidenced by the examples of worldwide commercial applications, utilizing, or recovering industrial low-grade heat (which is otherwise discharged to the environment) for useful work is possible by taking advantage of the state-of-the-art technologies discussed in this chapter. Inevitably, the number of commercial applications is still very limited, even though industrial waste heat is abundantly available and the concept of utilization or recovery is not new. This is because of resource constraints and lack of motivation due to the technical, regulatory, business, and organizational barriers as illustrated in **Figure 9**.

Technology	Advantage	Disadvantage
Adsorption [13]	<ul style="list-style-type: none"> Simple configuration without moving parts; eco-friendly refrigerants; and suitable for ultra-lowgrade heat recovery and utilization; high energy density of chemisorption 	<ul style="list-style-type: none"> Bulky; solid material related issues, e.g. poor heat and mass transfer within solid sorbent in the fixed bed; modest COP; temperature swing in the fixed bed and the sensible heat load of solid sorbent and metallic reactor; potential performance degradation; intermittency of the basic configuration; and lack of industrialization
Absorption [29]	<ul style="list-style-type: none"> Eco-friendly working fluid; reduce peak power demand; and mitigate greenhouse gas emission issues 	<ul style="list-style-type: none"> Large initial cost; and operational constraints; crystallization and corrosion issue of the working fluid
LDS [34, 36]	<ul style="list-style-type: none"> Effective air quality control; high density energy storage; can be driven by ultra-low grade heat 	<ul style="list-style-type: none"> Desiccant solution carryover leads to corrosion and high maintenance cost; and high thermal energy requirements for desiccant regeneration; low system efficiency; bulk system; system performance depends on atmospheric condition
ORC [41, 55]	<ul style="list-style-type: none"> Higher efficiency at low temperature and pressure; no blade erosion; and reduced maintenance 	<ul style="list-style-type: none"> Low efficiency and high cost for small scale application; and not environmental-friendly working fluid
Kalina cycle [47]	<ul style="list-style-type: none"> Improved heat transfer process and recuperation; common, bio-degradable and environmentally benign working fluid; and mature safety standards 	<ul style="list-style-type: none"> Complex circuit; unsuitable to be used with copper and copper alloys; and corrosive to mild steel and aluminum; and bulk system

Table 2. Advantages and disadvantages of the state-of-the-art technologies.

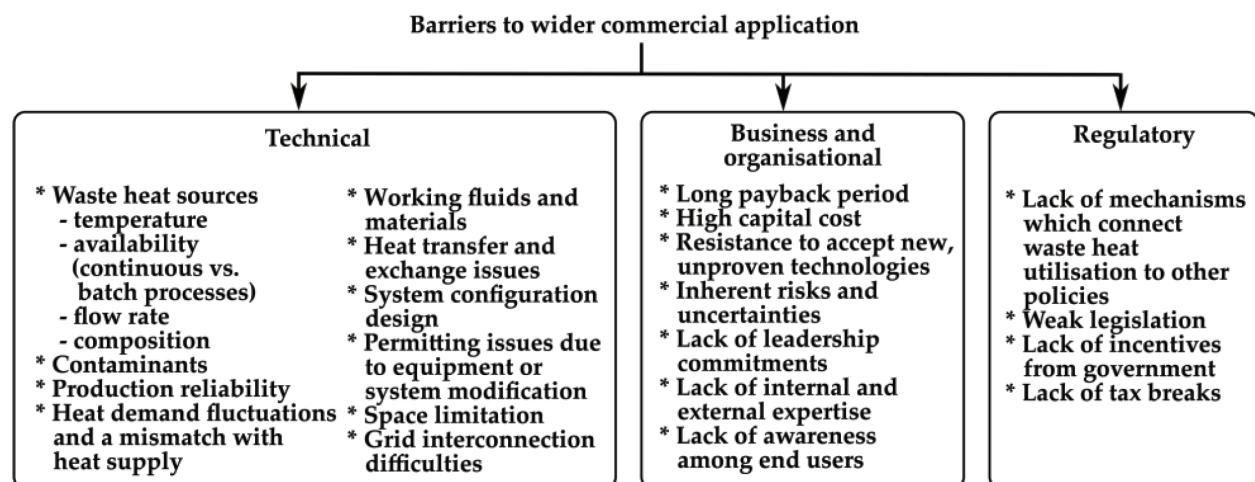


Figure 9. Technical, regulatory, business and organizational barriers to commercially deploying low-grade heat utilization and recovery technologies.

From a technical perspective, the varied nature of the low-grade heat sources including temperature, availability, flow rate, composition, contaminating content and working fluids affect the application significantly. From a business and organizational perspective, capital cost and payback period are the key factors considered by the management boards of industrial organizations. Currently, commercial applications are also hindered by the regulatory barriers such as the absence of financial incentives, tax breaks, strong policies and legislation.

Nevertheless, the successful stories of the existing commercial applications indicate more possibilities and opportunities in future. Indeed, they have set important precedents for feasible uptake of the technologies in various industry sectors. Opportunities present for wider commercial applications in future as a result of the following drives:

- a. Technical—R&D has been ongoing to (i) identify more working fluids from a wider range of fluid types and mixtures for different heat source temperatures; (ii) enhance heat transfer and exchange; and (iii) achieve optimal system performance.
- b. Economic—Significant energy cost savings are realized from the commercial applications in particular when energy prices soar.
- c. Business—The deployment of the state-of-the-art technologies is (i) justifiable on the grounds of improved corporate images when organizations endeavor in energy efficiency and sustainability; and (ii) possible for upcoming facility expansion and renovation while existing infrastructure can be used as a backup.
- d. Policy—Industrial willingness to go beyond business as usual can be stimulated by tax breaks or exemption and new feed-in tariffs for low-grade heat utilization and recovery.
- e. Information, training and knowledge transfer—More commercial applications can be realized provided manufacturers, dealers and technicians are informed about R&D advance on a regular basis.
- f. Social—The deployment brings along some advantages to the society, for instance, local/national economic development, new job opportunities, energy security, and indirect health benefits from reduced green house gas (GHG) emission.

Prior to commercial applications, the system must be designed with precautions and assessed thoroughly using a whole-system approach by taking account of technical, economic, legislative, social and environmental consideration. Life cycle assessment, which is a methodology widely applied for environmental assessment, is not further discussed but can be found in [56].

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